Radiation Effects and High-Field Magnets

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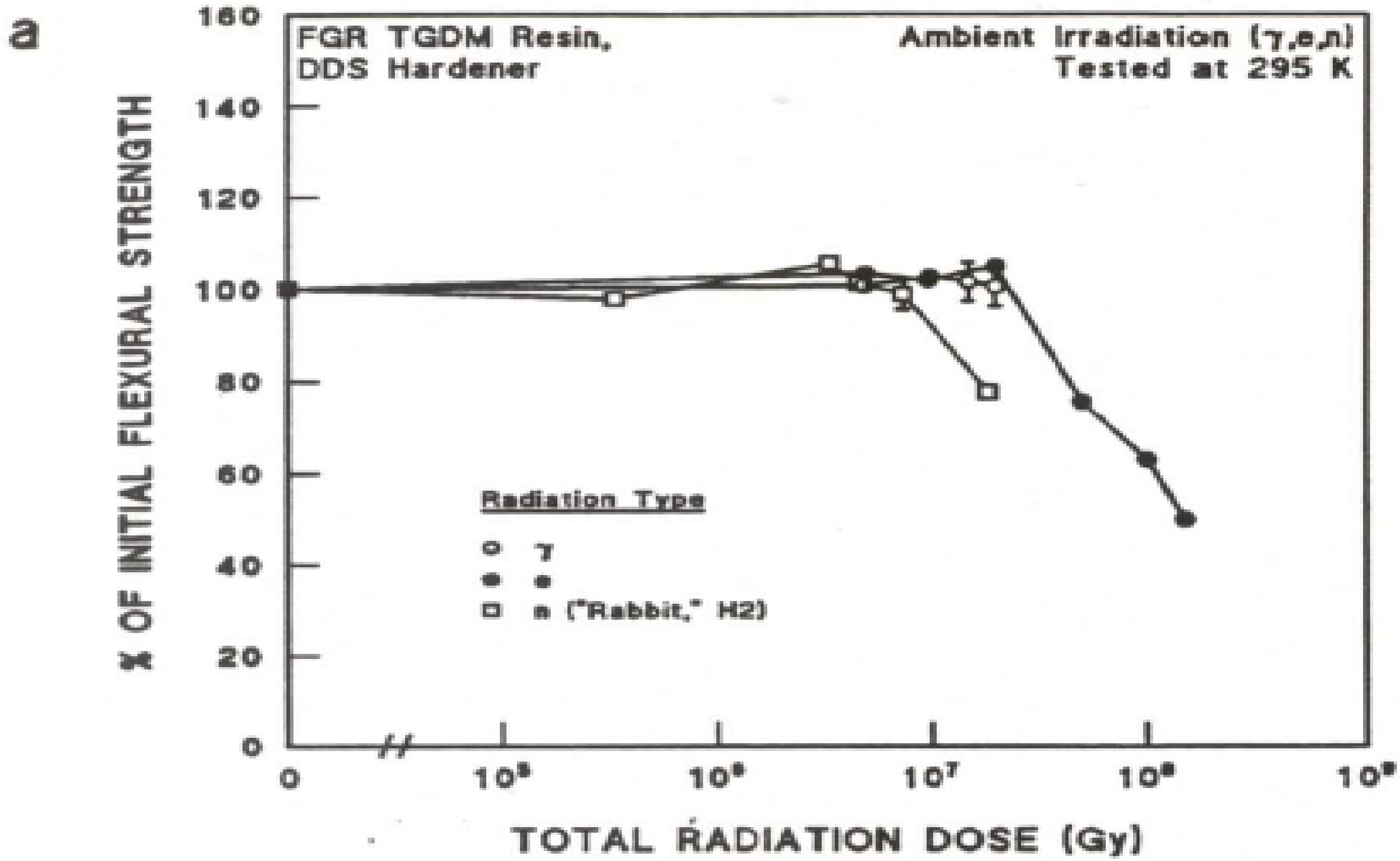
What do we need to build high-field magnets that have to operate in high radiation environments?

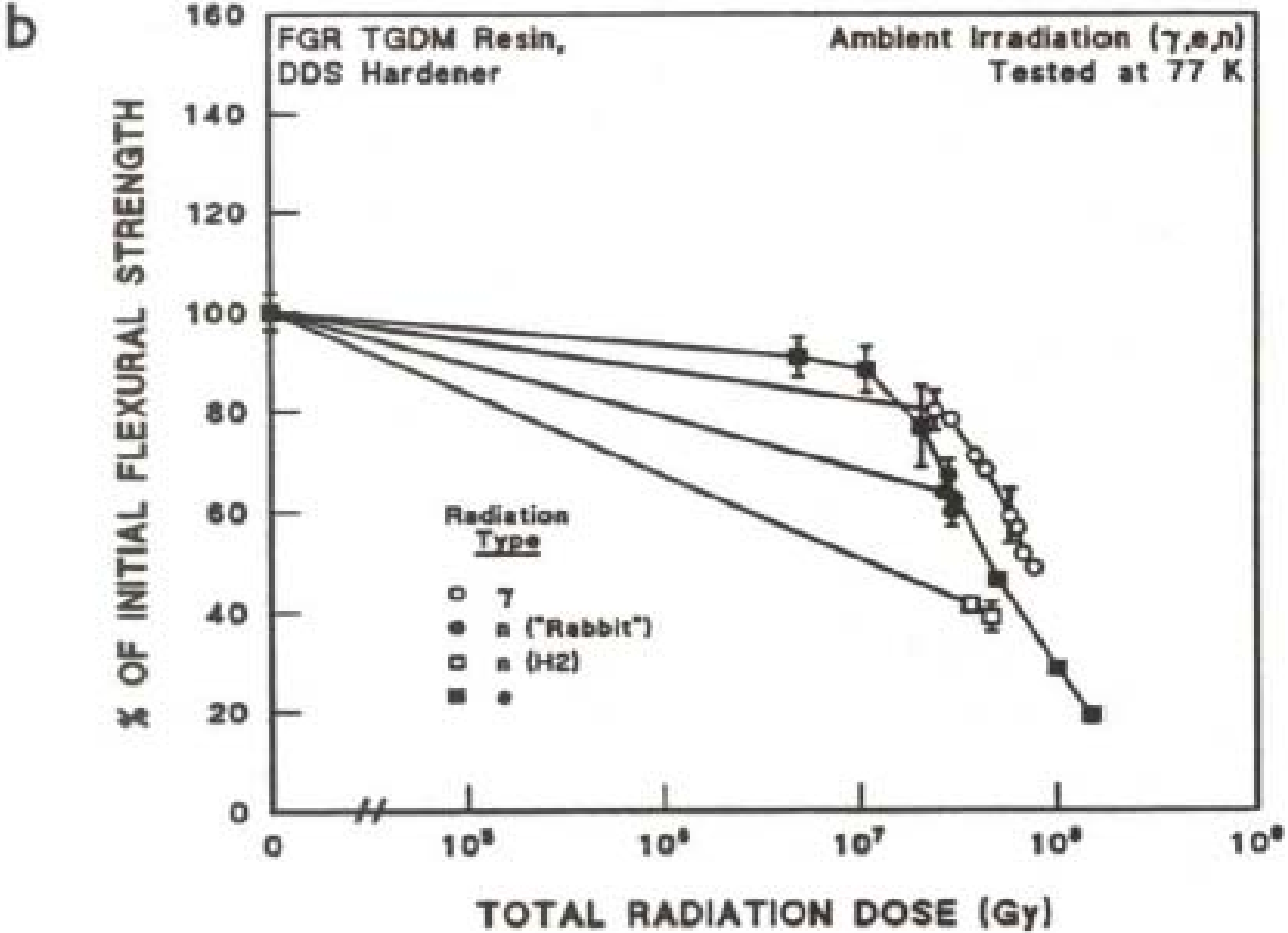
1. The right magnetic design (of course)
2. Expected radiation fields (MARS)
3. Expected life and thermal cycles

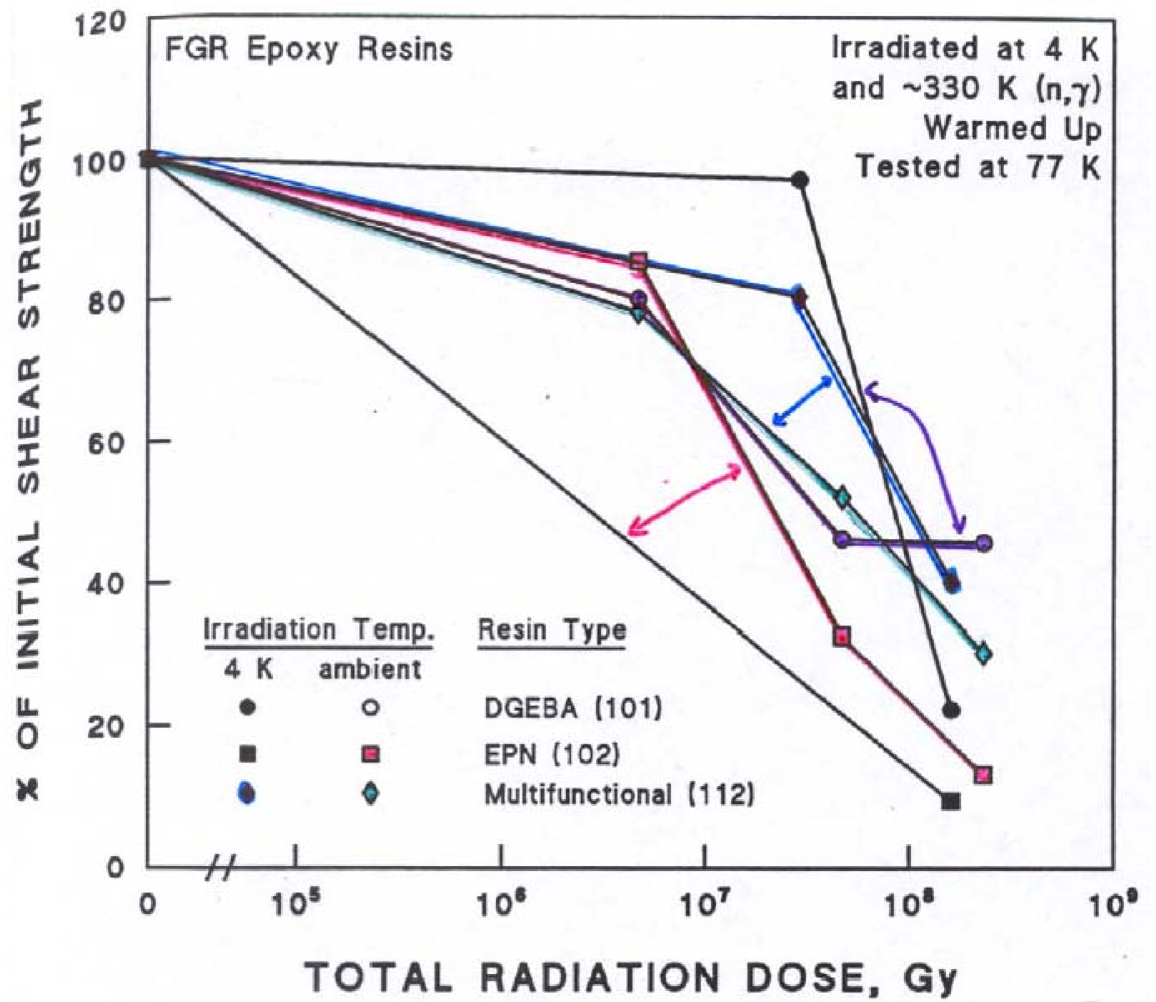
Need to examine all components that go into a magnet:

- Superconductor (Nb_3Sn)
- Insulation
- Copper
- Structural materials

Radiation field type and rate important



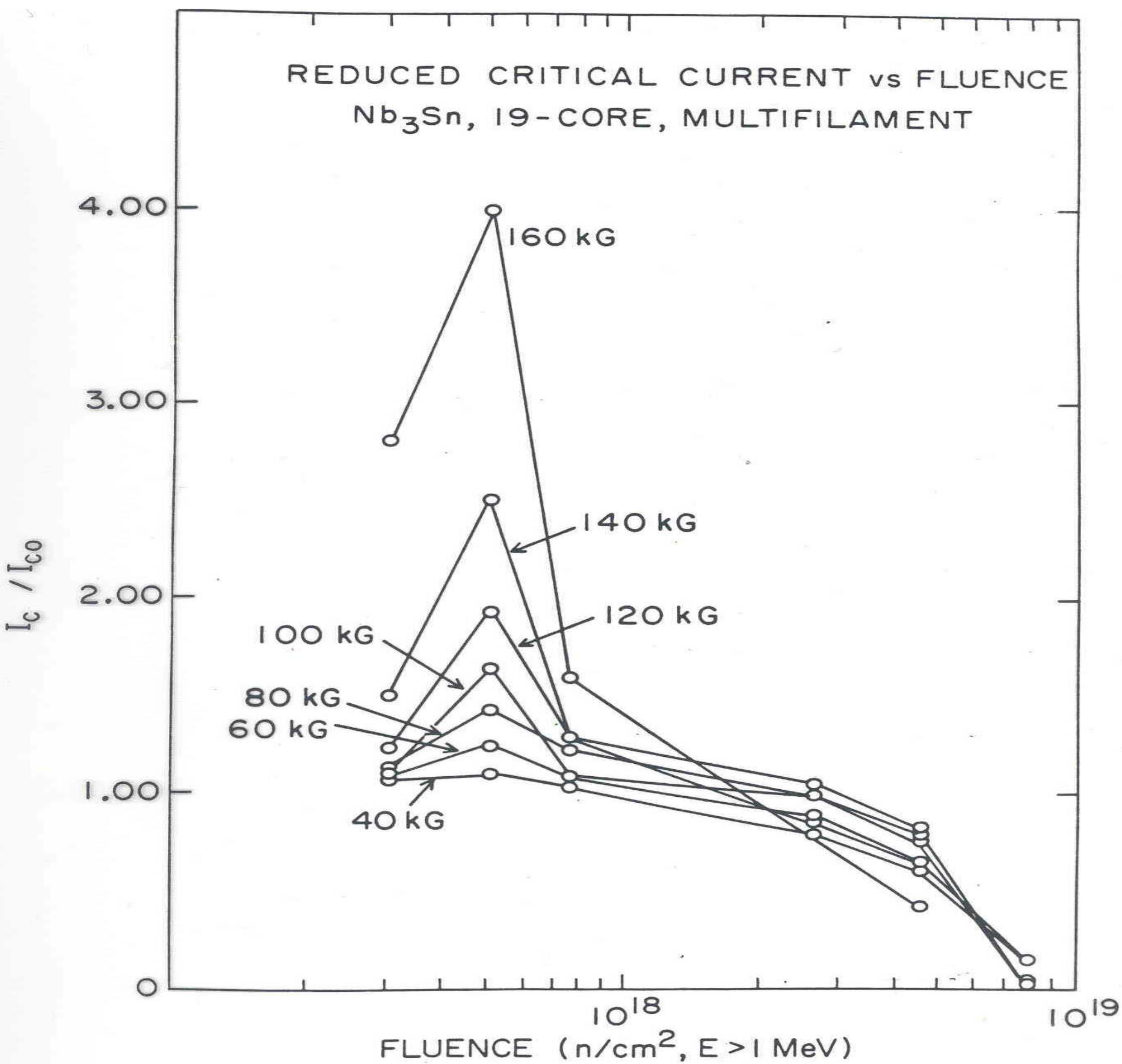

b
FGR TGDM Resin,
DDS Hardener
Ambient Irradiation (γ,e,n)
Tested at 77 K
% OF INITIAL FLEXURAL STRENGTH
160
140
120
100
80
60
40
20
0
Radiation
Type
γ
n ("Rabbit")
n (H2)
e
0
10^5
10^6
10^7
10^8
10^9
TOTAL RADIATION DOSE (Gy)



FGR Epoxy Resins
Irradiated at 4 K
and ~330 K (n,γ)
Warmed Up
Tested at 77 K
% OF INITIAL SHEAR STRENGTH
TOTAL RADIATION DOSE, Gy
120
100
80
60
40
20
0
0
10^5
10^6
10^7
10^8
10^9
Irradiation Temp.
4 K
ambient
Resin Type
DGEBA (101)
EPN (102)
Multifunctional (112)

Nb_3Sn

Unlike NbTi need to anneal at 700 C to regain critical current



REDUCED CRITICAL CURRENT vs FLUENCE
Nb3Sn, 19-CORE, MULTIFILAMENT
4.00
3.00
2.00
1.00
0
Ic / Ico
160 kG
140 kG
120 kG
100 kG
80 kG
60 kG
40 kG
10^18
10^19
FLUENCE (n/cm^2, E > 1 MeV)

Initial rise in J_c means you might be able to develop a more radiation tolerant material.

Possible problem with initial rise:

If radiation field is not uniform over the whole conductor, get spatial variation in J_c, which might affect field harmonics.

Note that radiation damage is like critical current in the peak field area: It is where coil will fail.

General limits for Nb_3Sn:

- **5 X 10^8 Gy (500MGy) end of life**
- **T_c goes to 5 K – 5 X 10^{23} n/m^2**
- **I_c goes to 0.9 I_{c0} at 14T – 1 X 10^{23} n/m^2**
- **B_{c2} goes to 14T - 3 X 10^{22} n/m^2**

NOTE: E_n < 14 MeV

Damage increases as neutron energy increases

Note:

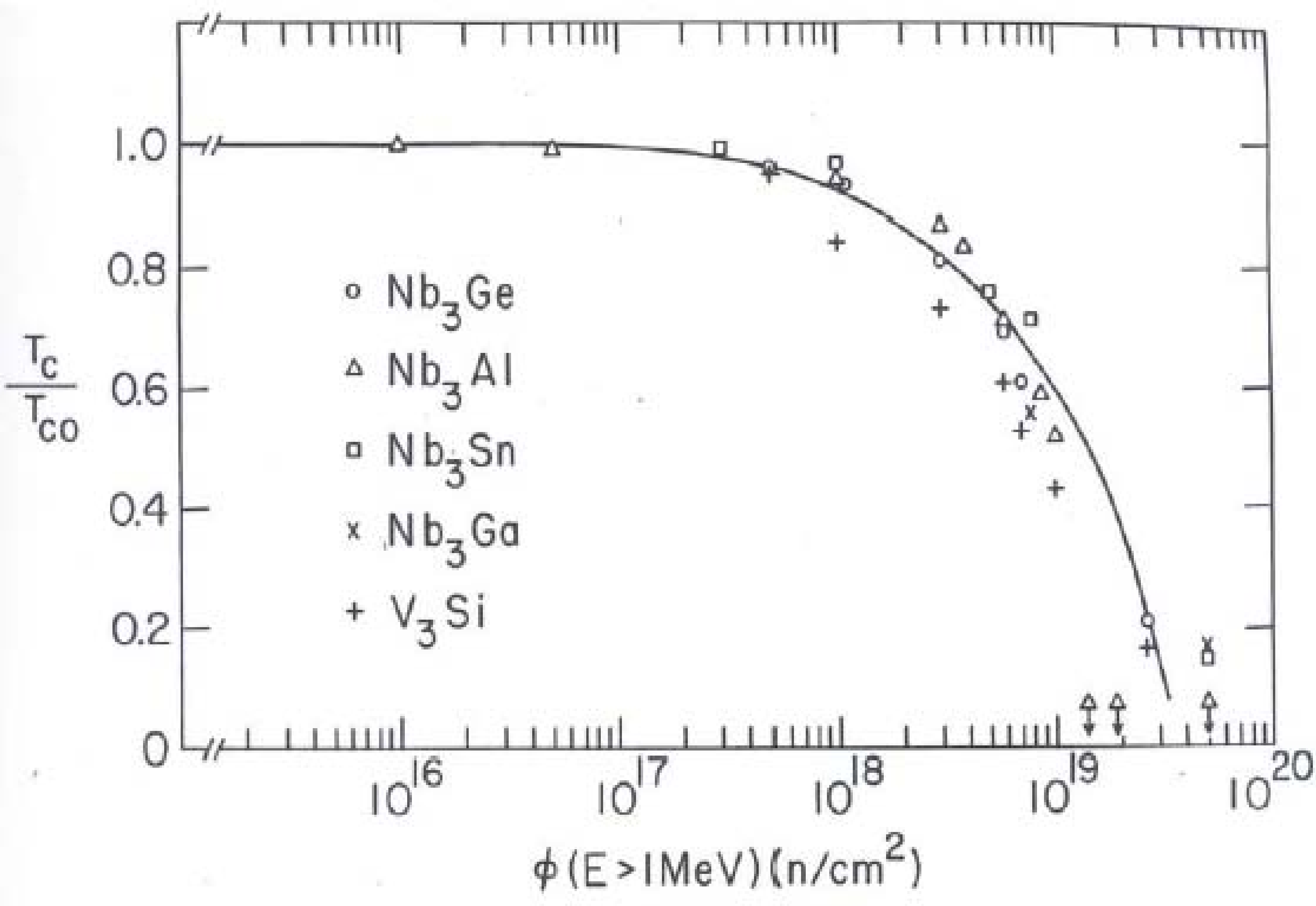
The above applies to long-term effects. There are short time-scale problems with high radiation heating.

Deposition of ~ 1 mJ/g may cause an immediate loss of stability. Even if the superconductor can tolerate this load, the refrigeration system may not.

1 mJ/g/s = 1 Gy/s

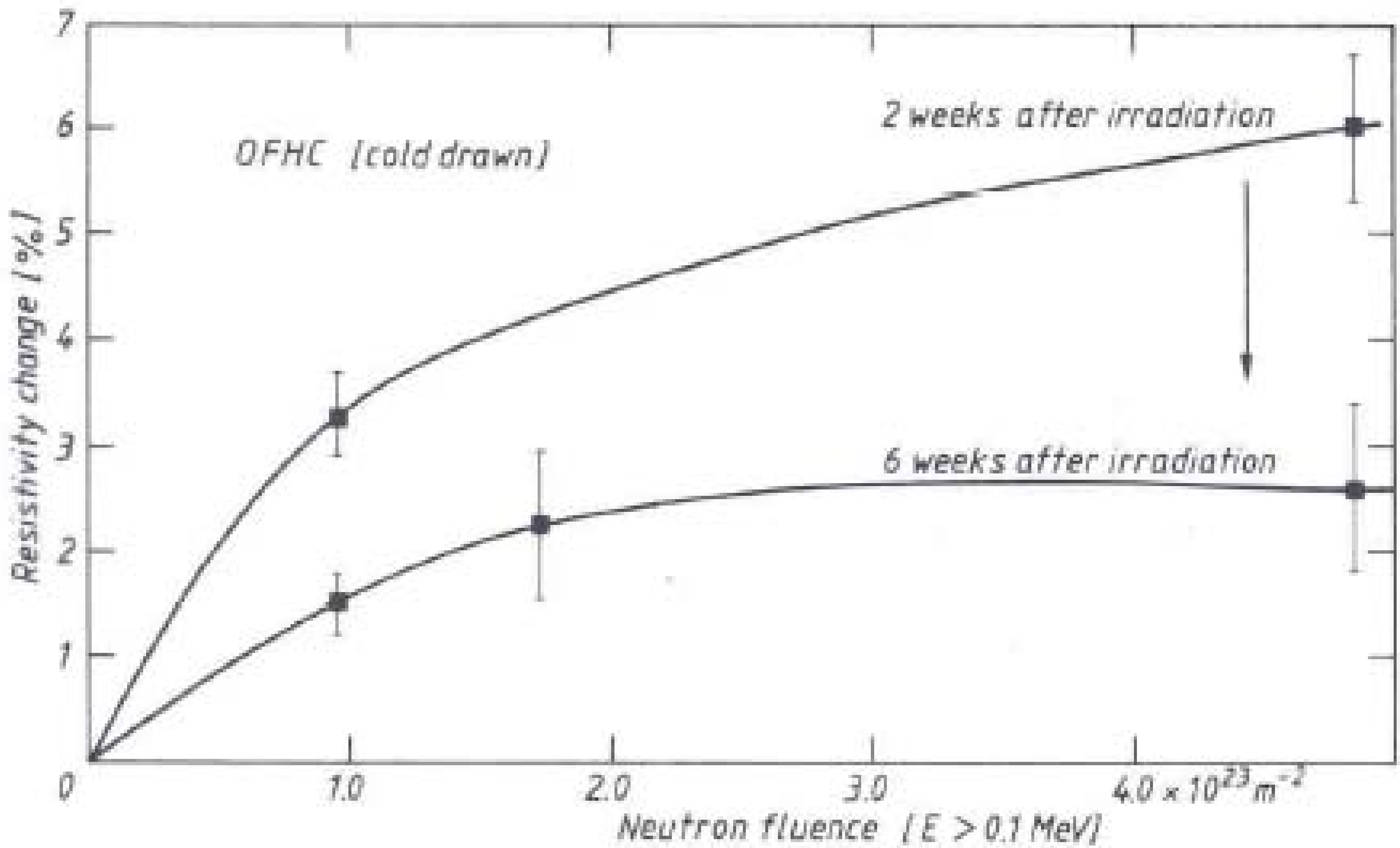
= 1 W/kg

At 4 K, this may be a substantial load.



1.0
0.8
0.6
0.4
0.2
0
$\frac{T_c}{T_{co}}$
Nb3Ge
Nb3Al
Nb3Sn
Nb3Ga
V3Si
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
$\phi(E > 1 MeV)(n/cm^2)$

Copper
Radiation increases resistance



Quench protection becomes an issue – lower allowed current in the copper or higher temperatures during a quench

Can anneal out 80-90% of the increased resistance by going to 300K

From the Wiedemann-Franz-Lorenz law at a constant temperature

$\lambda\rho$ = constant

Thermal conductivity decreases

Minimum propagating zone decreases:

$$L_{mpz} = \pi\sqrt{(\lambda(Tc-To)/\rho j^2)}$$

So $L_{mpz} \rightarrow \lambda$

Insulation

Wind-and-react uses inorganic sleeving (required to withstand reaction temperatures)
Provides space for impregnation

CTD epoxies fairly radiation resistant
~100 MGy

Problem:

Gas evolution
Ranges from 0.09 for Kapton to
>1 cm^3/g/MGy for other epoxies
Gas is released upon heating to room temperature

Can cause swelling, rupture of containment vessel or fracturing of epoxy

Warming to room temperature may be required to keep conductivity of copper high, but conflicts with gas evolution problems.

Would like space for helium, so strong porous material would be nice.

Ceramic slurry that is fired?

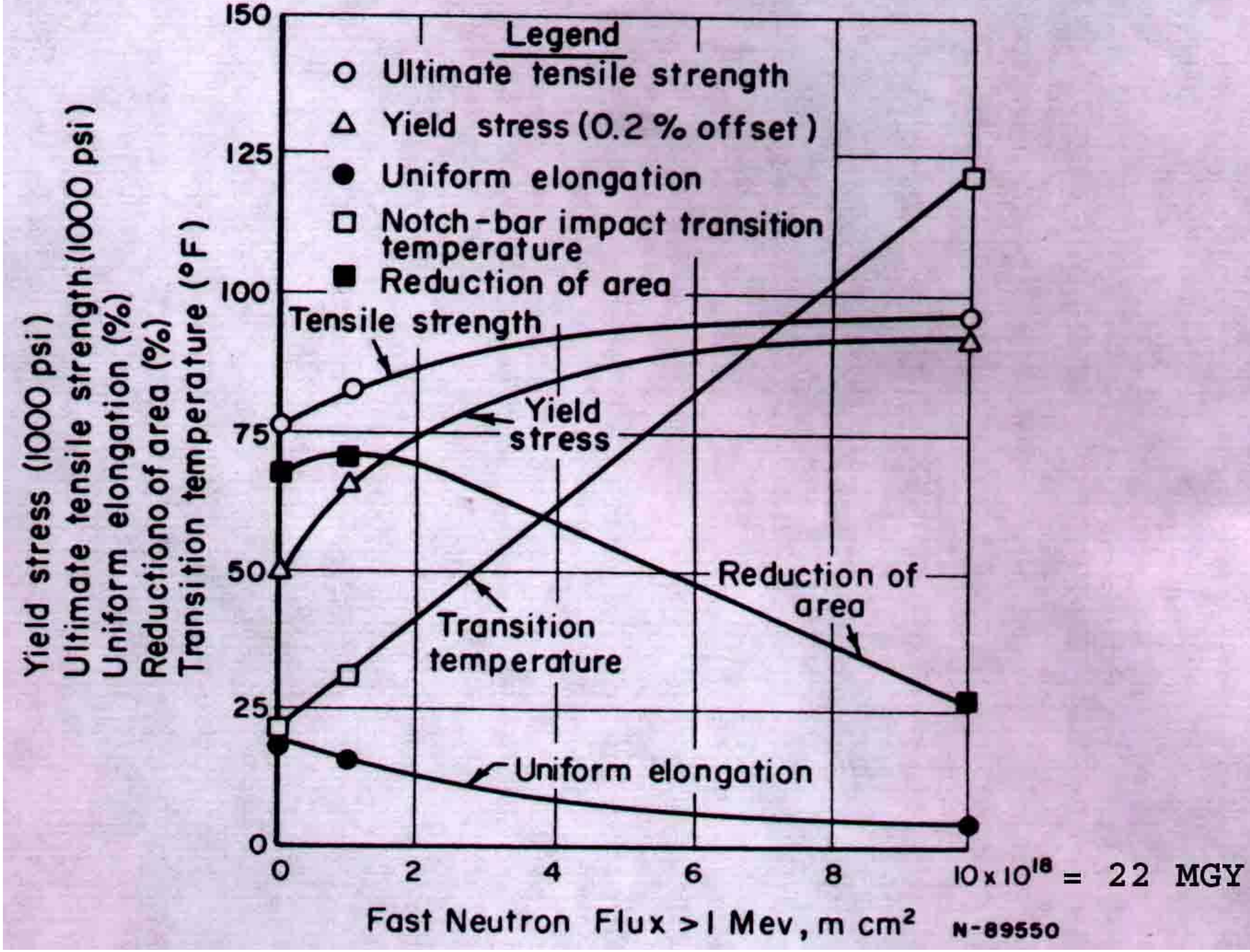
Differential contraction?

Structural materials

Crystal structure affect radiation sensitivity FCC materials (e.g. copper) less affected than BCC materials (e.g. iron)

Radiation causes dislocation pinning

- Decreases thermal conductivity
Increases ratio of yield-to-tensile strength (brittle)
- Generally makes material harder
- Decreases density (swelling)



Legend
Ultimate tensile strength
Yield stress (0.2 % offset)
Uniform elongation
Notch-bar impact transition temperature
Reduction of area
Tensile strength
Yield stress
Reduction of area
Transition temperature
Uniform elongation
Yield stress (1000 psi)
Ultimate tensile strength (1000 psi)
Uniform elongation (%)
Reductiono of area (%)
Transition temperature (°F)
150
125
100
75
50
25
0
0
2
4
6
8
10 x 10^18 = 22 MGY
Fast Neutron Flux >1 Mev, m cm²
N-89550

Ceramics

Exposure to ~ $10^{24} – 10^{25}$ n/m^2

Alumina: λ decreases by a factor of 4, density increased by 6.8%

BeO: Linear expansion of ~0.13%, Young's modulus decreases by 64%

Diamond: density decreases by 3.5%

Conclusions

1. Local radiation fields important
2. May need periodic warming to RT to maintain stability margin
3. Minimize insulator content May need to develop more radiation tolerant Nb_3Sn ($$$$)

Important Note

All of the radiation studies on $Nb^{3}Sn$ are 15-25 years old and we have lots of new materials.

Need new studies